# Asymmetries in core collapse supernovae revealed by maps of radioactive titanium

B. W. Grefenstette[1], F. A. Harrison[1], S. E. Boggs[2], S. P. Reynolds[3], C. L. Fryer[4], K. K. Madsen[1], D. R. Wik[5], A. Zoglauer[2], C. I. Ellinger[6], D. M. Alexander[7], H. An[8], D. Barret[9,10], F. E. Christensen[11], W. W. Craig[2,12], K. Forster[1], P. Giommi[13], C. J. Hailey[14], A. Hornstrup[11], V. M. Kaspi[8], T. Kitaguchi[15], J. E. Koglin[16], P. H. Mao[1], H. Miyasaka[1], K. Mori[14], M. Perri[13,17], M. J. Pivovaroff[12], S Puccetti[13,17], V. Rana[1], D. Stern[18], N. J. Westergaard[11], W. W. Zhang[5]

[1]Cahill Center for Astrophysics, 1216 E. California Blvd, California Institute of Technology, Pasadena, CA 91125, USA
[2]Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA
[3]Physics Department, NC State University, Raleigh, NC 27695, USA
[4]CCS-2, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[5]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[6]Department of Physics, University of Texas at Arlington, Arlington, TX 76019, USA
[7]Department of Physics, Durham University, Durham DH1 3LE, UK
[8]Department of Physics, McGill University, Rutherford Physics Building, Montreal, Quebec H3A 2T8, Canada
[9]Université de Toulouse, UPS-OMP, IRAP, Toulouse, France
[10]CNRS, Institut de Recherche en Astrophysique et Planétologie, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France
[11]DTU Space, National Space Institute, Technical University of Denmark, Elektrovej 327, DK-2800 Lyngby, Denmark
[12]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[13]ASI Science Data Center, Via del Politecnico snc I-00133, Roma, Italy
[14]Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[15]RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
[16]Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[17]INAF – Osservatorio Astronomico di Roma, via di Frascati 33, I-00040 Monteporzio, Italy
[18]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

**Asymmetry is required by most numerical simulations of stellar core collapse explosions, however the nature differs significantly among models. The spatial distribution of radioactive $^{44}$Ti, synthesized in an exploding star near the boundary between material falling back onto the collapsing core and that ejected into the surrounding medium[1], directly probes the explosion**

asymmetries.   Cassiopeia A is a young[2], nearby[3], core-collapse[4] remnant from which $^{44}$Ti emission has previously been detected[5-8], but not imaged. Asymmetries in the explosion have been indirectly inferred from a high ratio of observed $^{44}$Ti emission to that estimated from $^{56}$Ni[9], from optical light echoes[10], and by jet-like features seen in the X-ray[11] and optical[12] ejecta. Here we report on the spatial maps and spectral properties of $^{44}$Ti in Cassiopeia A. We find the $^{44}$Ti to be distributed non-uniformly in the un-shocked interior of the remnant. This may explain the unexpected lack of correlation between the $^{44}$Ti and iron X-ray emission, the latter only being visible in shock heated material. The observed spatial distribution rules out symmetric explosions even with a high level of convective mixing, as well as highly asymmetric bipolar explosions resulting from a fast rotating progenitor. Instead, these observations provide strong evidence for the development of low-mode convective instabilities in core-collapse supernovae.

$^{44}$Ti is produced in Silicon burning in the innermost regions of the material ejected in core-collapse supernovae, in the same processes that produce iron and $^{56}$Ni[13]. The decay of radioactive $^{44}$Ti (in the decay chain $^{44}$Ti->$^{44}$Sc->$^{44}$Ca) results in three lines of roughly equal intensity at 67.86, 78.36 and 1157 keV.  Previous detections by *COMPTEL*[5] of the 1157 keV line and *Beppo-SAX*[6], *RXTE*[7] and *INTEGRAL*[8] of the 68 and 78 keV lines were of relatively low statistical significance individually but when combined[8] they indicate a flux in each of the 67.86 and 78.36 keV lines of (2.3 +/- 0.3) x $10^{-5}$ ph cm$^{-2}$ s$^{-1}$. For an explosion date of 1671[2], distance of 3.4 kpc[3], and using

the half life of 60 years[14], this translates into a synthesized $^{44}$Ti mass of 1.6 $^{+0.6}_{-0.3}$ x

10$^{-4}$ M$_{Sun}$. Due to limited spectral and spatial resolution, previous observations are

not able to constrain the line centroid or spatial distribution within the remnant,

although the non-detection of the 1157 keV line by *INTEGRAL*/SPI has been used to

place a lower limit of 500 km/s on the line width.

The space-based *NuSTAR* (Nuclear Spectroscopic Telescope ARray) high-energy X-

ray telescope[15], which operates in the band from 3 – 79 keV, observed Cassiopeia A,

the remnant of a Type IIb supernova[4], for multiple epochs between August 2012 and

June 2013 with a total exposure of 1.2 Msec (Table ED1). The spectrum (Fig. 1)

shows two clear, resolved emission lines with centroids redshifted by ∼0.5 keV

relative to the rest frame $^{44}$Ti decays of 67.86 and 78.36 keV. The telescope optics

response cuts off at 78.39 keV (due to the Pt K-edge in the reflective coatings),

which may affect the measured line centroid, width, and flux of the 78.36 keV line,

so we focus on the 67.86 keV line for quantitative analysis. All errors are given at

90% confidence unless otherwise stated. We measure a line flux of 1.51 +/- 0.31 x

10$^{-5}$ ph cm$^{-2}$ s$^{-1}$, implying a $^{44}$Ti yield of  (1.25 +/- 0.3) x 10$^{-4}$ M$_{Sun}$. This confirms

previous spatially-integrated $^{44}$Ti yield measurements with a high statistical

significance (see Supplemental Information).  The $^{44}$Ti line is redshifted by 0.47 +/-

0.21 keV, corresponding to a bulk line-of-sight Doppler velocity of 1100 - 3000 km s$^{-1}$.  The line is also broadened with a Gaussian half width at half maximum (HWHM)

of 0.86 +/- 0.26 keV.  Assuming a uniformly expanding sphere the corresponding

velocity for the fastest material is 5350 +/- 1610 km/s.

The spatial distribution of emission in the 65 – 70 keV band (Fig. 2, Figure ED1) shows that the $^{44}$Ti is clumpy and is slightly extended along the 'jet' axis seen in in the X-ray Si/Mg emission[11] and fast moving optical knots[12]. There are also knots of emission clearly evident off the 'jet' axis. There is no evident alignment of the emission opposite to the direction of motion of the compact central object (CCO) as might be expected if the CCO kick involves an instability at the accretion shock[16].

We find that at least 80% (Figure ED2) of the observed $^{44}$Ti emission is contained within the reverse shock radius as projected on the plane of the sky. Assuming a ~5000 km/s expansion velocity from above and an age of 340 years, the fastest-moving, outermost material with the highest line-of-sight velocity is 1.8 +/- 0.5 pc from the center of the explosion, which is consistent with the 1.6 pc radius estimated for the reverse shock[17]. This rules out the possibility that the $^{44}$Ti is elongated along the line of sight and exterior to the reverse shock and is only observed in the interior of the remnant due to projection effects. We conclude that a majority of the $^{44}$Ti is in the un-shocked interior.

A striking feature of the *NuSTAR* $^{44}$Ti spatial distribution is the lack of correlation with the Fe-K emission measured by *Chandra* (Fig. 3). In a supernova explosion, incomplete Si burning produces ejecta enriched with a range of elements including Si and Fe, while 'pure' iron ejecta result either from complete Si burning or from the α-rich freezeout process that also produces $^{44}$Ti. While the fraction of Fe in 'pure'

ejecta is difficult to constrain observationally[18], most models predict that a significant fraction of the Fe is produced in close physical proximity to the $^{44}$Ti. Some correlation would therefore be expected. The simplest explanation for the lack of correlation is that much of the Fe-rich ejecta have not yet been penetrated by the reverse shock and therefore do not radiate in the X-ray band. While the X-rays from $^{44}$Ti decay are produced by a nuclear transition and directly trace the distribution of synthesized material, the Fe X-ray emission results from an atomic transition and traces the product of Fe density with the density of shock-heated electrons; without the hot electrons, the Fe will not be visible in the X-rays. A possible explanation of our observations is that the bulk of the Fe ejecta in Cassiopeia A have not yet been shock heated, further constraining models[18-20] of the remnant as well as the total amount of iron. An alternative explanation is that most of the Fe is already shocked and visible and some mechanism decouples the production of $^{44}$Ti and Fe and produces the observed uncorrelated spatial map.

Un-shocked or cool dense material (material that either was never heated, or has already cooled after being shock heated) might still be visible in the optical or infrared. The *Spitzer* space telescope observes line emission from interior ejecta primarily in [Si II] but it appears that there is not a significant amount of Fe present in these regions[21]. However, if un-shocked ejecta are of sufficiently low density or the wrong ionization states, then they will be invisible in the IR and optical. Low-density Fe-rich regions may in fact exist interior to the reverse shock radius as a

result of inflation of the emitting material by radioactivity (the "nickel bubble" effect[22]).

The concentration of Fe-rich ejecta inferred from maps in X-ray atomic transitions is well outside the region where it is synthesized, and not in the center of the remnant interior to the reverse shock. This observation has been used to suggest the operation of a strong instability similar to that proposed for SN 1993J[23]. The presence of a significant fraction of the $^{44}$Ti interior to the reverse shock and the implied presence of interior 'invisible' iron requires this conclusion be revisited.

The measured $^{44}$Ti line widths and distribution can directly constrain mixing in the supernova engine. As evidenced by SN1987A, mixing due to Rayleigh Taylor instabilities occurring between the explosion's forward and reverse shocks (distinct from the remnant's forward and reverse shocks) may be important in some types of supernova explosions[24]. Since $^{44}$Ti is a good spatial tracer of $^{56}$Ni in all established supernova models, we can compare the measured velocity width to that predicted for $^{56}$Ni by simulations. We find that the $\sim$5000 km/s maximum velocity and the level of Doppler line broadening compares well to Type IIb models including mixing[25] and excludes models without the growth of significant instabilities.

The evidence for asymmetries in the supernova explosion mechanism has grown steadily over the last decades. Asymmetries are implied by a number of observations[26]: the extensive mixing implied in nearby supernovae (e.g. SN 1987A);

the high space velocities of neutron stars; and the polarization of supernova emission. Although different external processes could separately explain each of these observations, it is generally assumed that the asymmetries arise in the explosion mechanism. Within the convectively-enhanced supernova engine paradigm a number of mechanisms have been proposed[27]: asymmetric collapse, asymmetries caused by rotation, and asymmetries caused by low-mode convection. Of these, rotation and low-mode convection have received the most attention. Rotation tends to produce bipolar explosions along the rotation axis where the ejecta velocities are two to four times greater along this axis[28] than in the rest of the ejecta. Low-mode convection, including the standing accretion shock instability (SASI), will produce a bipolar explosion in fast-rotating stars, but is likely to produce higher order modes in slowly-rotating systems[29].

To further understand the nature of the observed $^{44}$Ti non-uniformity, we compare the observations to three-dimensional models of normal core collapse supernovae using a progenitor designed to produce the high $^{44}$Ti/$^{56}$Ni ratio needed to match the estimated yields in the Cas A remnant. We simulate two explosions that represent the extremes of explosion asymmetry: a spherically symmetric explosion and an explosion representing a fast-rotating progenitor with artificially-induced bipolar asymmetry where the explosion velocity in a thirty-degree half-angle cone near the rotation axis is increased by a factor of four relative to the rest of the ejecta. The simulated $^{44}$Ti maps (Figure ED3) indicate that the level of observed non-uniformity in Cassiopeia A is far greater than what can be produced by the spherically

symmetric explosion and that the bipolar explosion (where the bulk of the fast [44]Ti remains within 30 degrees of the rotation axis) cannot reproduce the observed off-axis [44]Ti knots. This argues against fast-rotating progenitors as well as jet-like explosions, which are even more collimated than the bipolar explosions. The supernova is better described by an intermediate case, where the observed non-uniformity in the [44]Ti is the result of a multi-modal explosion such as predicted in both low-mode Rayleigh-Taylor models[29] and Standing Accretion Shock Instability models[30]. The Cassiopeia A remnant provides the first strong evidence that this low-mode convection must occur.

**Methods Summary:**

A full description of the methods, including data analysis, background modeling, error estimates, and supernovae simulations can be found in the Supplemental Information.

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*NuSTAR* Operations, Software and Calibration teams for support with execution and analysis of these observations.

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**Figure 1**: **The broadband hard X-ray spectrum of Cassiopeia A.**  Data from both

telescopes over all epochs are combined and shown as the grey data points with 1-**σ**

error bars. The spectra are shown combined and rebinned for plotting purposes

only.  Also shown are the best-fit continuum models for a power law (blue) and a

model that describes electron cooling due to synchrotron losses (red). The

continuum fits were obtained using the 10 - 60 keV data and extrapolated to 79 keV

with the best-fit values for the continuum models provided in Table ED2, though the

choice of continuum model does not significant affect the measurement of the lines

(see Supplemental Information for details).

**Inset**: Zoomed region around the $^{44}$Ti lines showing the data and the two models on

a linear scale.  The vertical green lines are the rest-frame energies of the $^{44}$Ti lines

(67.86 keV and 78.36 keV).  A significant shift of ~0.5 keV to lower energy is evident

for both lines, indicating a bulk line-of-sight velocity away from the observer. Details

of the data analysis, including a discussion of the *NuSTAR* background features

(Figure ED4), are given in the Supplemental Information. When the continuum is

extrapolated to 79 keV there are clearly visible line features (Figure ED5) near the

$^{44}$Ti line energies. Table ED3 lists the parameters of the best-fit Gaussian models of

these features with the error estimates described in the Supplemental Information.

**Figure 2: A comparison of the spatial distribution of the [44]Ti with the known "jet" structure in Cassiopeia A.** The image is oriented in standard astronomical coordinates as shown by the compass in the lower left and spans just over 5 arcminutes. The [44]Ti observed by *NuSTAR* is shown in blue, where the data have been smoothed by a top-hat function with a radius shown in the lower right (dashed circle). The [44]Ti is clearly resolved into distinct knots and is non-uniformly distributed and almost entirely contained within the central 100 arcseconds (see the Supplemental Information and Figure ED2). Shown for context in green is the *Chandra* ratio image of the Si/Mg band (data courtesy NASA/CXC, Si/Mg ratio image courtesy J. Vink), which highlights the jet/counterjet structure, the center of the expansion of the explosion[2] (yellow cross), and the direction of motion of the compact object (white arrow). In contrast to the bipolar feature seen in the spatial distribution of Si ejecta that argues for fast rotation or a jet-like explosion, the distribution of [44]Ti is much less elongated and contains knots of emission off of the jet axis. A reason for this may be that the Si originates from the outer stellar layers and is likely highly influenced by asymmetries in the circumstellar medium, unlike the [44]Ti, which is produced in the innermost layers near the collapsing core.

**Figure 3: A comparison of the spatial distribution of [44]Ti with known Fe K emission in Cassiopeia A.** We reproduce the spatial distributions shown in Fig 2 and add the 4 to 6 keV continuum emission (white) and the spatial distribution of X-ray bright Fe (red) seen by *Chandra* (Fe distribution courtesy U. Hwang). We find that the [44]Ti does not follow the distribution of Fe-K X-ray emission, suggesting

either that a significant amount of Fe remains un-shocked and therefore does not radiate in the X-ray, or the Fe/Ti ratio in the ejecta deviates from the expectation of standard nucleosynthesis models.

**Figure ED1: The background-subtracted image of Cas A in the 65 to 70 keV band containing the 68 keV [44]Ti line showing the significance of the [44]Ti knots.** The data have been smoothed with a 20-arcsecond-radius top hat function (dashed circle) and are shown with 3 and 4 sigma significance contours (green). In addition to the features shown in Figure 1 we also show locations of the forward (R ≈ 150 arcseconds) and reverse (R ≈ 100 arcseconds) shocks[17] (white dashed circles) for context. The [44]Ti clearly resolves into several significantly identified clumps that are non-uniformly distributed around the center of expansion.

**Figure ED2: The radial profile of the [44]Ti emission.** We collect each photon in annular bins of increasing radius in the plane of the sky without any spatial smoothing. **Panel A:** The radial profiles of the [44]Ti the data in the 65 to 70 keV (black) and the radial profile expected from the background images (red), scaled by the area of each annulus and shown in units of counts / arcsec$^2$. **Panel B:** The background-subtracted radial profile. **Panel C:** The percent of enclosed flux in annuli of increasing radii as observed on the plane of the sky. All error bars are 1-sigma.

**Figure ED3**: **Simulated ⁴⁴Ti intensity contours for a symmetric and a bipolar explosion.** The vertical line shows a 4' scale (note the different spatial scale between the symmetric (left) and bipolar (right) explosions). The non-uniformities in the observed ⁴⁴Ti spatial distribution rule out the purely symmetric explosion, even with extensive mixing. Similarly, the presence of ⁴⁴Ti outside of the "jet" axis argues against the rapidly rotating progenitor that produced the bipolar explosion. We therefore argue that the explosion that produced Cassiopeia A is somewhere between these two extremes and that this is the first clear example of a low-mode convection explosion.

**Figure ED4: The background spectral model fit for one of the Cas A epochs**. Shown are the data from the background regions (black points with 1-sigma error bars included but not visible), the instrumental background (green), the CXB components (blue, dashed is the focused CXB component), the phenomenological "source" model (magenta), and the total background model (red). **Inset:** The background spectrum near the ⁴⁴Ti emission lines showing the features that we model. The broad lines at 65 and 75 keV are likely neutron capture emission features, while the narrow line near 67 keV is an internal activation line in the CdZnTe detectors. See supplemental information for more details.

**Figure ED5: The significant signals observed in the spectrum near 68 and 78 keV. Panel a:** The black points (1-sigma error bars) are the data shown after the background model spectrum has been subtracted from the source data. The red

continuum is the best-fit powerlaw continuum over the 20-80 keV band-pass. **Panel b:** The contribution to the C-stat statistics for each spectral bin. The large signals near 68 and 78 keV (the [44]Ti emission lines) suggest that an additional spectral component is required. See supplemental information for details.

**Table ED1: List of observations used in this analysis**. Start/stop dates are given, as has the effective exposure of each observation. The exposure has been corrected for period when the source was occulted by the earth, periods where the instrument was not taking data, and for the rate-dependent livetime of the instrument.

**Table ED2: Best-fit continuum parameters.** Results for the considered continuum models. Error ranges for the parameters are given at the 90% level.

**Table ED3: Results from spectral analysis.** Results for all three spectral models for the [44]Ti emission are given with 90% error estimates from the background Monte Carlo analysis. Errors are the statistical estimates from the fit parameters and do not include the systematic uncertainties in the *NuSTAR* effective area.